

InP MATERIALS/CELL FABRICATION

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This report describes the main points of discussion, conclusions, and recommendations of the Workshop on InP held at the NASA SPRAT conference. An unusual level of interest in this workshop was shown with 37 delegates being in attendance. The names, affiliations and telephone numbers of these persons are shown in Appendix I.

The meeting commenced with a presentation by the chairman (T.J. Coutts), of issues he believed are central to the development of InP as a solar cell absorber. The object of this was to stimulate subsequent discussion in the anticipation that the topic may be relatively unfamiliar to most of the attendees. A copy of all slides used in the chairman's presentation is given in Appendix II. The key points emerging from the workshop were summarized on the final morning of the conference. The viewgraphs used for this presentation are also appended.

I. Chairman's Presentation

It is considered that it will become important to assess the quality of p-InP crystals supplied by different vendors, whether they are to be used as an active part of the device or as a substrate for the growth of epi-layers. At present very few manufacturers will deliver moderately doped (10^{15} - 10^{17} cm⁻³) p-type material. Only five have been found so far (slide 4). At SERI, the analyses shown in slide 5 can now be routinely performed and the capabilities are being extended systematically. Examples of photoluminescence (PL) measurement of minority carrier lifetime and its variation with impurity concentration are shown in (slides 6 and 7). PL has also been used to assess

the effect of low power rf plasma exposure of substrates and typical spectra are shown in slide 8. Cathodoluminescence (CL) has also been used to examine the surfaces of freshly prepared substrates. Slide 9 shows the presence of many non-radiative defects. In future, attempts will be made to profile the depth distribution of the defects and to minimize their density using different preparation/conditions. It is also planned to use high resolution cross-sectional transmission electron microscopy using a newly acquired ion-milling machine.

The issue of back contacts to solar cells is one frequently ignored by researchers, but in reality it is of great importance. In slide 10 the obvious parameters influencing the contact resistance are shown and in slide 11 the areas which, it is considered, should be studied. Such investigations are now well underway at SERI and initial results are beginning to clarify the changes shown in slide 12. The nature of the junction formation was then discussed and a review of substrate cleaning techniques was presented; see slides 13, 14, 15. Generally, the effectiveness of cleaning techniques is not quantified, but the group at SERI (under NASA support) is currently using monochromatic ellipsometry (in-house) and spectroscopic ellipsometry (in conjunction with D. Aspnes of Bell Labs) to investigate native oxides and surface roughness. An example of native oxide growth after cleaning is shown in slide 16. Using techniques developed more recently, residual oxide thicknesses have been reduced below 10 Å. Slide 17 shows the Raman spectrum (performed by F. Pollack's group at Brooklyn College) of a freshly polished substrate. The line width indicates minimal surface damage and residual strain. Hence, it seems possible that substrate preparation techniques are adequate to produce reasonable devices, but the CL study shows that there is room for improvement in substrate quality.

Techniques for junction formation were then discussed and it was pointed out that the largest values of V_{oc} had been achieved by the group at Arizona State University, using a p- on n-substrate; slides 18, 19. A photoreflectance spectrum of an ITO/InP junction prepared by (ion-beam) sputtering is shown in slide 20 (obtained at Brooklyn College), and the sharpness of the features again indicates that reasonable quality devices are being made.

Techniques like this should be applied by other workers using different fabrication methods.

An estimate of the maximum probable AM1.5, 100 mW cm⁻² efficiency was then made (slide 21). This was 23%; i.e., approximately equal to that of GaAs devices. It was pointed out that further improvements will probably depend on the development of cells grown by OMCVD. SERI and several other groups are now investigating this possibility. Technological aspects of optimized grid-ding and AR coatings were then discussed (slides 23, 24, 25, 26). SERI has put considerable effort into these topics over the duration of the NASA contract and it is expected that this ground work will be very valuable when good quality junctions are being produced. Slide 28 shows a summary of the highest efficiencies reported in the literature for InP based cells.

Finally, in slide 29 other issues were raised. Not least of these is the question of reporting efficiencies accurately. It was emphasized that there is a great need to report AMO data for cells of realistic area and under well defined experimental conditions; and to report only total area efficiencies. Issues were also raised on the reliability of radiation resistance data; on the cost of InP (this is falling, but needs to fall much further), and on the chemical stability of significant interfaces. Under the category "Others", issues related to increasing the power/mass ratio, utilizing concentrator systems, the use of non-InP substrates for epi-films etc were raised. Discussion of these will be left until the end of the report on the main points emerging from the workshop conversations, subsequent to these opening remarks by the chairman.

II. Workshop Discussions

2.1 Need to Increase Efficiency of InP Based Cells

At present, the highest efficiency reported for an InP based cell is around 15% (AMO). This is based on a calculation performed by I. Weinberg of NASA Lewis Research Center on a result reported by the Japanese group at N.T.T. Although 15% is very encouraging, the device cannot really be taken seriously until substantial improvements have been made; despite its excellent radiation resistance. There is scope for improvement in J_{sc} , V_{oc} and fill-

factor, but particularly in the first two of these. The largest value of AM1.5, 100 mW cm^{-2} reported is 27.7 mA cm^{-2} (ITO/InP discussed by Coutts at this meeting). From the spectral response of this cell it was calculated that J_{sc} at AM0 would be 33.5 mA cm^{-2} which for an 8% grid coverage, translates to 36.5 mA cm^{-2} active area. With improved gridding and AR coating, an upper limit of 37 mA cm^{-2} would seem realistic, for the total area. This is equivalent to 90% x the maximum theoretical value which is comparable to that achieved for more mature technologies.

There was extensive discussion about the maximum achievable V_{oc} . Finally a value of $0.7 \times E_g = 945 \text{ mV}$ was agreed upon, again by comparison with GaAs. The highest V_{oc} reported to date is 845 mV (by Shen et al, at this meeting) so, as with J_{sc} , there is an estimated improvement of about 10-12% to be made.

If such an improvement in V_{oc} were made there would also be a significant gain in FF, and an estimate of 85% was made for the practicable maximum. Hence, the participants of the workshop believed that a well-funded program on InP cells could ultimately lead to an AM0 efficiency of 21.7%. This rather startling figure caused a reconsideration, based on intuition, and one or two participants felt that 20.5% was perhaps a more realistic target. Earlier in the meeting, Goradia had made a similar prediction.

2.2 Means of Improving Efficiency

Although InP is usually believed to have a low surface recombination velocity, it was suggested that passivation would nevertheless, lead to further significant gains in V_{oc} . A lattice matched ternary window layer to InP, analogous to AlGaAs/GaAs, is a possibility, and one which may be appropriate is AlAsSb. The disadvantage of this material is that it may be difficult to grow an abrupt AlAsSb/InP interface. Assuming that the devices are ultimately based on epitaxially grown InP, the transition to AlAsSb will of necessity be more demanding than that from GaAs to AlGaAs. Considerable effort has been made to passivate the surface of InP with various insulators for MISFET's. Varying degrees of success have been achieved and this is another area worth studying in the present context. It may, for example, be possible to fabricate devices based on the PESC design used for Si cells.

Advances could also be made using deeper junctions but this would necessitate a substantial improvement in the materials properties and, in particular, in the minority carrier lifetime. Improvements in material quality of substrates were also believed to be important and the need to characterize crystals supplied by different vendors was emphasized.

Finally, there are substantial improvements to be made in efficiency merely through better gridding and A.R. coatings. The internal quantum efficiency of many devices is already high, but substantial losses result from lack of attention to processing aspects.

2.3 Efficiency Measurements

At present, efficiencies quoted in the literature tend to lack any standardized form. Worse, it is not always clear whether a particular measurement refers to AM0, AM1, AM1.5 or some other air mass number, what simulator was used, whether total or active area was used, and what the measurement temperature was. Hence, workers in the field are encouraged, at least, to specify their measurement conditions accurately. A further preference was expressed that measurements should all refer to AM0, since these cells are more likely to be used for space, rather than terrestrial applications.

Finally, the view was expressed that data would be much more significant if larger area devices were made. Clearly, much greater inaccuracies result for small area cells. An acceptable area was, however, not defined, but areas greater than 0.3 cm^2 are to be preferred.

2.4 Radiation Testing

The present high level of interest in InP based cells results from their excellent radiation resistance. It is necessary, therefore, that these results (mainly of the Japanese group) be confirmed. It is also necessary to perform the radiation tests on devices of as high efficiency as are available. This is particularly relevant since there are indications that radiation resistance may be a function of impurity concentration, which in turn influences efficiency. Hence, it may be that high efficiency and high radiation resistance are mutually exclusive.

In this context, radiation damage models should be developed to identify the defects leading to degradation, and to account for the apparently high radiation resistance.

This has also raised the issue that there may be materials with even greater radiation resistance than InP. Might it be possible to predict these in advance rather than devoting years of study to a less than optimum material?

2.5 Future Developments

At some point it will be necessary to increase the power/mass ratio of these cells. To date, only cursory studies have been made and it may be advisable to initiate more thorough systems studies at an early date.

Since cost is of pre-eminent importance (as stressed by J. Scott-Monck in the final workshop presentation of this conference) a reduction in the cost of InP is necessary. Early consultations with substrate suppliers could therefore be advantageous and could lead to forecasts of cost/supply. Alternatively, studies of InP growth on other low cost substrates would seem to be a promising area, even if technically complicated. CLEFT studies could also lead to cost reductions and, funding permitting, should be pursued.

Finally, concentrator studies should be initiated with a view to determining cost and system design considerations. This could include determining the optimum concentration ratio, the reduction in radiation damage by the concentrator optics etc.